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Flat-Plate
Solar Array Project

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Sensitivity Analysis of the Add-On Price Estimate for the Silicon Web Growth Process

Anant R. Mokashi

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The JPL Flat-Plate Solar Array Project is sponsored by the Department of Energy (DOE) and forms part of the Photovoltaic Energy Systems Program to initiate a major effort toward the development of cost-competitive solar arrays.

ABSTRACT

The web growth process is a silicon-sheet technology option that is being developed for the Flat-Plate Solar Array (FSA) Project, which is sponsored by the U.S. Department of Energy.

In order to achieve the FSA price goal of $\$0.70/W_p$, certain required production-rate and sheet-quality standards must be met. Based on research and development experience, base-case data for the technical and cost parameters that could be achieved for the technical and commercial readiness phase of the FSA project are projected.

This study presents a sensitivity analysis of the process add-on price, using the base-case data in terms of cost parameters such as equipment, space, direct labor, materials and utilities, and the production parameters such as growth rate and run length, using a computer program developed specifically to do the sensitivity analysis with Improved Price Estimation Guidelines. The sensitivity analysis is also performed with respect to silicon price, sheet thickness and cell efficiency.

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EXECUTIVE SUMMARY

The web growth process is one of the silicon-sheet technology options that is being developed by Westinghouse R&D Center (WRDC) for the Flat-Plate Solar Array (FSA) Project, sponsored by the U.S. Department of Energy. The add-on price goal for the web process is $38.60/m^2 or $0.29/W_p at an encapsulated cell efficiency of 14.0%. This is consistent with the FSA Project price goal of $0.70/W_p (1980 $) for photovoltaic modules with efficiency of 13.3%.

The present study performs a sensitivity analysis of the process add-on price in terms of cost parameters such as equipment, space, direct labor, materials and utilities, and production parameters such as growth rate and run length. The sensitivity analysis is also performed with respect to silicon price, sheet thickness and cell efficiency. The computer program developed specifically for doing the sensitivity analysis with Interim Price Estimation Guidelines (IPEG) is used in this study.

The add-on price for the process is estimated at $22.82/m^2, based on the data provided by WRDC for the projected web technology. The breakdown of the add-on price of $22.82/m^2 in terms of the cost parameters indicates that the primary cost driver is direct labor, which contributes 37.5[illegible]% of the price with the assumption of 18 furnaces per operator (FPO). The sensitivity analysis shows that by varying the FPO from 6 to 24 the price is reduced from $39.97/m^2 to $20.67/m^2 and the corresponding direct-labor contribution is substantially reduced, from 64% to 31%. By increasing the FPO to 30, the price and labor contribution are reduced to $19.39/m^2 and 26.54%, respectively, which is of marginal benefit. Contribution of equipment cost to the price is 33.72%, which is nearly equivalent to that of direct labor.

The web technology has been developed remarkably by Westinghouse R&D Center during the last five years. No serious technical problems are foreseen in meeting the Technical Readiness goal of $0.70/W_p. Several conceptual approaches exist to enhance this technology further, leading to a $0.50/W_p level. Research and development efforts required for this should be initiated soon.

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SECTION I

INTRODUCTION

The Flat-Plate Solar Array (FSA) project, sponsored by the U.S. Department of Energy, has responsibility for developing photovoltaic solar array technology to make it technically feasible and commercially viable. The project goals are to achieve Technical Readiness for producing photovoltaic modules at the price of $\$0.70/W_p$ by 1982, and to achieve Commercial Readiness by 1986. (All monetary figures in this document are in 1980 dollars.)

Developing the technology for manufacturing large-area silicon sheets is one of the tasks in the Technology Development Area of the FSA Project. Several sheet-growth technologies are being developed in parallel under this task; the silicon web growth process is one of them. The Westinghouse R&D Center (WRDC) has been working on web process development for the FSA Project since 1974.

The web process is described briefly thus: Polycrystalline silicon, as pellets or in similar form, is fed into a quartz crucible and is melted by heating the crucible in a furnace. The furnace consists of a molybdenum susceptor and heat shields. The growth process is initiated from a thin wire-like seed, which is brought into contact with the molten metal in the crucible through a slot in the susceptor cover. The seed front grows laterally to form a button. The seed is withdrawn and dendrites continue from the ends of the button in the melt. The web is formed by the solidification of the liquid film formed between the dendrites and the button. The width reaches a steady state determined by the thermal conditions in the melt. The ribbon is withdrawn and rolled on a reel. Thickness, width and growth rate are functions of the dimensions of the slot in the susceptor cover and the thermal factors.

Much attention has been given to automating the process to minimize the direct labor requirement. It will be shown below that direct labor is web's primary cost driver, contributing 38% of the add-on price of the process.

According to the Price Allocation Guidelines (Reference 1), the add-on price goal for the web process is $\$38.6/m^2$. At the present level of demonstrated technology, the price estimate is several times higher than the goal.

A detailed cost analysis (References 2 and 3) was done by WRDC (1978 to 1980) using an earlier version of the Interim Price Estimation Guidelines (IPEG) (Reference 4). The results of the previous studies are updated, the computation of direct labor cost has been improved and the more recent version of IPEG (Reference 5) is used in the present study.

It is desirable to perform a sensitivity analysis of the estimated price in terms of production rate and cost parameters. Given the add-on price of the web process, based on WRDC projected data, the sensitivity analysis is performed with respect to silicon price, sheet thickness and cell efficiency. SAIPEG, a computer program especially developed to perform the sensitivity

analysis, using IPEG, is used in this study. The results will aid in identifying the primary cost drivers and the sensitivity range of variations in the important parameters. This information will help in setting the direction of future technology development efforts.

SECTION II

SENSITIVITY ANALYSIS USING IPEG (SAIPEG)

The add-on price of any standard assembly-line process is estimated by using the SAMICS (Reference 6) procedure and the SAMIS (Reference 7) program developed by JPL. The computer cost of using SAMIS is on the order of $100 per run. The use of SAMICS/SAMIS procedure for doing a sensitivity analysis of a process involving large numbers of runs is therefore prohibitively expensive. The price estimation using the IPEG procedure is considered to be of sufficient accuracy to do the sensitivity analysis.

SAIPEG is a computer program (written in FORTRAN) for doing the sensitivity analysis using IPEG; the SAIPEG procedure is described below.

A. PRICE ESTIMATION

The IPEG2 (improved version of IPEG, Reference 5) equation used in the current study is:

$$AMC = C1 \times EQPT + C2 \times AREA + C3 \times DLAB + C4 \times (MATS + UTIL) \qquad (1)$$

where

AMC	=	Annual Manufacturing Cost ($/yr). (Required annual revenue and AMC are used interchangeably.)
EQPT	=	Total installed cost of the equipment ($).
AREA	=	Area required by the process equipment and its operators for the production unit (ft^2).
DLAB	=	Annual cost of direct labor ($/yr).
MATS	=	Annual cost of materials and supplies ($/yr).
UTIL	=	Annual cost of utilities ($/yr).
C1	=	The coefficient corresponding to EQPT, a function of the Equipment Lifetime (ELT). ELT is assumed in this study to be the same for all equipment.

C1 = 0.83 for ELT of 3 years,
= 0.65 for ELT of 5 years,
= 0.57 for ELT of 7 years,
= 0.52 for ELT of 10 years,
= 0.48 for ELT of 15 years, and
= 0.46 for ELT of 20 years.

C2 = The coefficient corresponding to AREA ($\$/ft^2/yr$).

$C2 = 109.0$

C3 = The coefficient corresponding to DLAB, varying with labor pay rates used in computing DLAB (including fringe benefits, or not):

$C3 = 2.1$ if fringe benefits are included in DLAB and
$= 2.8$ if fringe benefits are not included.

C4 = The coefficient corresponding to TMATS and UTIL.

$C4 = 1.2.$

EQPT, AREA, DLAB, MATS and UTIL are referred to as cost parameters. The add-on price is estimated as follows:

$$\text{PRICE } (\$/m^2) = \text{AMC } (\$)/\text{QTYPYR } (m^2) \tag{2}$$

where

QTYPYR = The quantity of sheet produced per year (m^2/yr).

B. INPUT DATA

The cost parameters and the quantity produced per year are in turn computed using the basic data for the process as described below. The input data for the example considered are given in Table 1.

C. PRODUCTION

$$\text{RNPYR} = (365 - \text{DTPYNP}) \times 24/\text{RNLNHR} \tag{3}$$

$$\text{DTCY} = \text{RNLNHR} - (\text{ECLT} + \text{HMSGT} + \text{TGCDT})/\text{RNLNHR} \tag{4}$$

$$\text{QTYPRN} = \text{RBWCM} \times \text{GRCMPM} \times \text{RNLNHR} \times \text{RBPF} \times \text{FPPU} \times \text{PRYL} \times \text{DTCY} \times (60.0 \times 0.0001) \tag{5}$$

and

$$\text{QTYPYR} = \text{QTYPRN} \times \text{RNPYR} \tag{6}$$

where

RNLNHR = Run length in hours. This includes:

(1) Equipment cleaning and loading time.

(2) Heating, melting and start-of-growth time.

Table 1. Base-Case Input Data for the Add-On Price Estimate Using SAMPEG

PRODUCTION		
Number of furnaces per production unit	(FPPU)	1.00
Number of ribbons per furnace	(RBPF)	1.00
Ribbon width (cm)	(RBWCM)	5.00
Growth rate (cm/min)	(GRCMPM)	5.00
Run length (h)	(RNLNHR)	72.00
Equipment cleaning and loading time (h)	(ECLT)	1.00
Heating, melting and start-of-growth time (h)	(HMSGT)	3.00
Termination-of-growth and cool-down time (h)	(TGCDT)	3.00
Nonproductive downtime per year (days)	(DTPYNP)	14.00
Process yield	(PRYL)	1.00
EQUIPMENT		
Furnace ($/each) (based on purchase of 100)	(FRNC)	15,400.00
Equipment lifetime (yr)	(ELT)	7.00
AREA		
Area for one furnace unit (ft^2)	(ARPF)	30.00
DIRECT LABOR		
Fringe benefits included	(FRBNIN)	No
Labor pay rate ($/h)	(PRTLB)	6.30
Number of furnaces per operator	(FPO)	18.00
MATERIALS		
Crucible ($/furnace)	(CRCBL)	14.00
Crucible lifetime (runs)	(CRLT)	1.00
Furnace argon flow rate (ft^3/h/furnace)	(FAFR)	2.00
Argon rate ($/100 ft^3)	(ARGPR)	4.20
UTILITIES		
Furnace power consumption (kW/furnace)	(FURPC)	3.00
Electricity power rate ($/kWh)	(EPRT)	0.05

(3) Automated silicon web growth.

(4) Termination of growth and cool-down time.

DTPYNP = Nonproductive down time per year. This time is used for annual repair and preventive maintenance.

RNPYR = Number of runs per year (see Equation 3).

ECLT = Equipment cleaning and loading time (h).

HMSGT = Heating, melting, and start-of-growth time (h).

TGCDT = Termination-of-growth and cool-down time (h).

DTCY = Duty cycle, the ratio of the actual production time (h) to RNLNHR, obtained by Equation 4. Annual repair and maintenance time (DTPYNP) is excluded from the definition of the duty cycle.

RBWCM = Ribbon width in cm.

GRCMPM = Growth rate in cm/min.

RBPF = Number of ribbons per furnace.

FPPU = Number of furnaces per production unit. For convenience of comparison with various data sets, FPPU is considered to be unity.

PRYL = Process yield. This is expressed as quantity sellable/quantity produced. In this study, PRYL is considered to be unity as the quantity produced is computed excluding the dendrites, etc. Non-uniformity of sheet during the start of growth, etc., is accounted for in the duty cycle.

QTYPRN = Quantity of silicon sheet produced per run. (60.0 x 0.0001) is the conversion factor for converting cm^2/min to m^2/h.

QTYPYR = Quantity of silicon sheet produced per year. This is the product of QTYPRN and RNPYR.

D. EQUIPMENT

$$EQPT = FRNC \tag{7}$$

where

FRNC = Furnace cost ($/furnace). This is estimated on the assumption that 100 machines are bought.

E. AREA

$$AREA = ARPF \times FPPU \tag{8}$$

where

ARPF = The area required for each process equipment unit and its operators (ft^2/furnace).

F. DIRECT LABOR

$$OPPU = FPPU/FPO \tag{9}$$

$$DLAB = OPPU \times PRTLB \times 40 \times 52.142 \times (365 - DTPYNP) \times 24/1760 \tag{10}$$

where

OPPU = Number of operators per production unit per shift.

FPO = Number of furnaces operated by one operator. FPO will have value less than unity if more than one operator is required to operate the equipment (furnace).

DLAB = The annual cost of direct labor ($/yr). The following assumptions are made in computing DLAB (Reference 4):

(a) A year consists of 52 1/7 weeks (365 days).

(b) A week consists of five days with eight working hours per day (40 h/week).

(c) Allowing for eight days of paid holidays and 13% absenteeism due to vacations, illness and other paid leave, a person works for 220 days per year.

Based on the above assumptions, the number of person-years required for three shifts (continuous operation) is computed by multiplying the number of person-years required per shift by a factor which is three times the ratio obtained by the number of working days per year (365 - DTPYNP) divided by 220.

PRTLB = Labor Pay Rate ($/h). It should be specified whether or not the PRTLB includes fringe benefits to determine the appropriate coefficient to be used in computing AMC.

G. MATERIAL

$$CRBLYR = (CRCBL \times RNPYR \times FPPU)/CRLT \tag{11}$$

PWCY = RNLNHR - (ECLT + TGCDT)/RNLNHR (12)

FAY = (ARGPR/100) x FAFR x WHPY x PWCY x FPPU (13)

TMATS = CRBLYR + FAY (14)

where

PWCY = Power cycle. This is the fraction of run time during which the power is on.

CRBLYR = Cost of crucibles required ($/yr).

CRCBL = Cost of crucibles ($/furnace).

CRLT = Crucible lifetime (runs).

FAY = Cost of furnace argon ($/yr).

ARGPR = Cost of argon ($/100 ft^3).

FAFR = Furnace argon flow rate (ft^3/h/furnace).

WHPY = Working hours per year of the furnace. WHPY is the product of run length in hours (RNLNHR) and the number of runs per year (RNPYR).

H. UTILITIES

FRPWYR = EPRT x FURPC x WHPY x PWCY x FPPU (15)

UTIL = FRPWYR (16)

where

FRPWYR = Cost of furnace power consumption ($/yr).

EPRT = Electric power price ($/kWh).

FURPC = Furnace power consumption (kW/furnace).

Equations (3) to (16) provide the information required for computing the AMC and the production rate, which in turn are used in Equation (2) for price estimation. The results for the base-case data are presented in Table 2. The breakdown of the estimated price in terms of contributions from each cost parameter and also in percentage is given in Table 2. The SAIPEG program can be used to compute the price with different sets of input data. The sensitivity analysis capability of the SAIPEG program is described below.

Table 2. Price Estimation Results Using Base-Case Data

PRODUCTION RATE

Production quantity per run (m^2)	9.75
Production quantity per year (m^2)	1,140.75

COST PARAMETERS AND COEFFICIENTS

Parameter	Quantity	Coefficient
Equipment ($)	15,400	C1 = 0.57
Area (ft^2)	30	C2 = 109.00
Direct labor ($)	3,494	C3 = 2.80
Materials ($)	2,306	C4 = 1.20
Utilities ($)	1,193	C5 = C4

REQUIRED ANNUAL REVENUE

Annual manufacturing costs (AMC) ($/yr)	26,030.81

ADD-ON PRICE ESTIMATE AND ITS BREAKDOWN

Parameter	$/$m^2$	%
Equipment	7.695	33.722
Area	2.867	12.562
Direct Labor	8.576	37.583
Materials	2.426	10.632
Utilities	1.255	5.501
Total Price	22.819	100.000

The base-case data refer to a machine growing one ribbon 5 cm wide, at a rate of 5 cm/min. It is assumed that 18 such machines are operated by one person.

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SECTION III

SENSITIVITY ANALYSIS

The SAIPEG program can perform a sensitivity analysis of the process add-on price as a function of the production rate or of any of the cost parameters within a specified range with known increments. The sensitivity analysis is performed with respect either to the production rate or to any of the cost parameters, varied one at a time with the rest of the data held constant. The production rate and the cost parameters in turn are varied by changing some of the basic input parameters, as described below. Given the process add-on price, the sensitivity analysis is performed by varying the silicon price, and other parameters such as sheet thickness and cell efficiency.

A. PRODUCTION RATE

The production rate is varied by changing any of the two basic parameters: (a) run length (RNLNHR) and (b) growth rate (cm^2/min). For the fixed value of RNLNHR, the growth rate is changed from a specified minimum value to a specified maximum value with a desired increment. For each value of the growth rate, the add-on price is computed and growth rate vs add-on price is plotted. The procedure is repeated for each RNLNHR specified. The results for the example studied are discussed below.

B. EQUIPMENT

The contribution of equipment to AMC is calculated by varying (a) equipment lifetime and (b) equipment cost. For a given lifetime of equipment, the equipment cost (EQPT) is varied from a minimum value to a maximum value with specified increments. For each value of equipment cost the add-on price is estimated and the graph of equipment cost vs add-on price is plotted. The procedure is repeated for all of the values of equipment life of interest.

C. AREA, MATERIAL, AND UTILITIES

For each of these cost parameters the corresponding contributions to AMC are varied from minimum to maximum values with specified increments. The add-on price is estimated for each value of a parameter and parameter vs add-on price is plotted. Sensitivity analysis is performed with respect to one parameter at a time.

D. DIRECT LABOR

The contribution of DLAB to AMC is varied by changing two of the basic input parameters: (a) labor pay rate (PRTLB), and (b) the number of furnaces operated per operator (FPO). For a specified PRTLB, FPO is varied from a minimum to the specified maximum with desired increments. For each value of FPO, add-on price is computed and FPO vs add-on price is plotted. The procedure is repeated for each value of PRTLB of interest.

E. SILICON PRICE

The add-on price of the web silicon sheet process ($\$/m^2$) is computed ignoring the cost of silicon. The total price of sheet should include the cost of silicon material. The Silicon Material Task of the FSA Project is working on the problems of reducing the silicon price. The sensitivity analysis is performed by varying the silicon price. Other parameters varied are sheet thickness and cell efficiency. For the fixed value of sheet thickness and cell efficiency, the add-on price is computed in terms of $\$/W_p$ and silicon price vs add-on price is plotted. The procedure is repeated for each combination of sheet thickness and cell efficiency specified.

The total add-on price for sheet is computed as follows:

PR1 = WFP/(INSC x ECE x CY)

PR2 = SIP x TH x CONF x SILDN/(INSC x ECE x CY x SWY)

PRICE = PR1 + PR2

where

WFP	=	Web sheet process add-on price in $\$/m^2$.
INSC	=	Insolation constant (assumed to be 1000 W/m^2).
ECE	=	Encapsulated cell efficiency.
CY	=	Sheet to cell yield.
SWY	=	Silicon to sheet yield.
SILDN	=	Silicon density (2330 kg/m^3).
CONF	=	Conversion factor for converting mils to meters (0.0000254).
TH	=	Sheet thickness in mils.
SIP	=	Silicon price in ($/kg).
PR1	=	Web process add-on price in $\$/W_p$.
PR2	=	Silicon material add-on price in $\$/W_p$.
PRICE	=	Total sheet add-on price in $\$/W_p$ including cost of silicon.

It may be noted that the sensitivity analysis with respect to any of the cost parameters can be repeated for each value of the DTCY and PRYL and their specific combination of interest. Data and the results are discussed in the next section.

SECTION IV

SAIPEG RESULTS FOR THE WEB PROCESS

Data for the economic analysis of the web process are being generated and continuously updated, based on technology development experience. Westinghouse R&D Center has demonstrated ribbon growth as wide as 4.4 cm and growth speeds as high as 6.7 cm/min. Melt replenishment has been incorporated in the design of the furnace. A machine capable of growing ribbon 5 cm wide at a speed of 5 cm/min is being developed. The base-case data provided in Table 1 reflect the projected values for a machine of desired production rate. The data have been grouped by production rate and the five cost parameters.

IPEG price estimation results based on the base-case data of Table 1 are presented in Table 2. It is estimated that 1140.75 m^2 of silicon sheet would be produced per machine per year at a cost of \$26,031, resulting in an add-on price of \$22.82/m^2. The composition of AMC in terms of the cost parameters and the corresponding coefficients are given in Table 2. The add-on price breakdown in terms of cost parameter contributions is presented in Table 2. Direct labor is the primary cost driver, contributing 38% of the add-on price; utilities contribute only 5%. The contribution of equipment cost is 34% of the add-on price, and the contributions of area and materials are 12% and 11% respectively.

The estimated add-on price of \$22.82/m^2 with the projected data is below the FSA Project goal of \$38.6/m^2 for the web process. If technical development is achieved according to the projections, the web process more than meets the project goals. Because of the inherent uncertainty of such projections, the sensitivity of the add-on price with respect to the production rate, the cost parameters, and the silicon price is of interest. The results of the sensitivity analysis are presented below.

A. PRODUCTION RATE

For this analysis, run length is varied from 1 day to 5 days with 1-day increments. Growth rate is varied from 10 cm^2/min to 40 cm^2/min with increments of 5 cm^2/min. The base-case datum for run length is 3 days and for the growth rate is 25 cm^2/min. The variation of run length in turn affects the number of furnaces operated by one operator. The furnaces are in automatic growth mode during most of the time of run length. The operator uses his time performing two functions: (a) cleaning, loading and start of growth, and (b) surveillance of furnaces in automatic mode. The time required for function (a) per furnace per run is assumed to be 2 hours. If an operator starts two furnaces per shift he uses his time equally for functions (a) and (b) and at the end of one day six furnaces will be operating. If the run length is 3 days, furnaces per operator (FPO) will be 18 and FPO will be 24 and 30 for run lengths of 4 and 5 days, respectively. It is assumed that 4 hours of operators time per shift will be enough for function (b) for FPO as high as 30. For shorter run lengths of 1 and 2 days, FPO will be 6 and 12 respectively and the time used for function (b) becomes excessive. For run

length of one day, 3 furnaces can be started per shift and FPO can be 9 instead of 6. The same holds for run length of 2 days. FPO of 15 is also considered assuming that 2.5 machines are started per shift. All of these cases have been considered in the analysis. The results of add-on price vs area growth rate with run length as a parameter are shown in Figure 1.

It is observed in Figure 1 that the price goal is met with growth rate as low as 15 cm^2/min for run length of 3 days. Area growth rates of 36 cm^2/min and 28.5cm^2/min for FPO 6 and 9, respectively, will be necessary to meet the price goal for run length of 1 day. For run length of 1 to 3 days, the process is labor-intensive, with labor cost contributing to 60% to 38% of the price, respectively. If the run length is increased to 5 days, the labor contribution is reduced to 27%. For run length of 4 days, the add-on price variation with FPO 22 or 24 is negligible. Similarly, for run length of 5 days, the add-on price variation is not significant when FPO is changed from 25 to 30. It is observed that the curves are asymptotic. For run length of three days or more, the reduction in add-on price for a growth rate more than 30 cm^2/min is marginal. WRDC has demonstrated both web width of 5 cm and growth rate of 5 cm/min, but not simultaneously except for a short period. Efforts should be concentrated on achieving a steady state of growth for run lengths as long as 3 days at a rate of 25 cm^2/min.

B. COST OF EQUIPMENT

The cost of equipment for the base-case data in Table 1 is $15,400 and the lifetime of the equipment is 7 years. It is observed in Table 2 that nearly one third of the add-on price is contributed by the equipment cost. Equipment cost should be reduced if possible. The cost of equipment is varied by considering the life of equipment to be 3, 5, 7, 10, 15 and 20 years; for each of the assumed lifetimes the cost varies from $5,000 to $30,000, with increments of $5,000. The graph of add-on price vs equipment cost is shown in Figure 2. For equipment of 3 years' lifetime, cost can be as high as $30,000 and still meet the goal. For equipment of more than 3 years lifetime, the cost can be higher than $30,000 and still meet the goal.

C. AREA, MATERIALS AND UTILITIES COSTS

The base-case value for area is 30 ft^2 per machine, contributing 12% of the add-on price. Area required is varied from 10 ft^2 to 60 ft^2. The graph of area vs add-on price is given in Figure 3. The area can be increased to 60 ft^2 without exceeding the price goal.

The cost of materials for the base case is $2,306, contributing only 11% of the add-on price. The graph of materials cost vs add-on price is shown in Figure 4. For materials cost as high as $4,000, the add-on price is still below the price goal.

The base-case data give $1,193 as utilities cost, contributing only 5% to the add-on price. The add-on price is least influenced by this parameter.

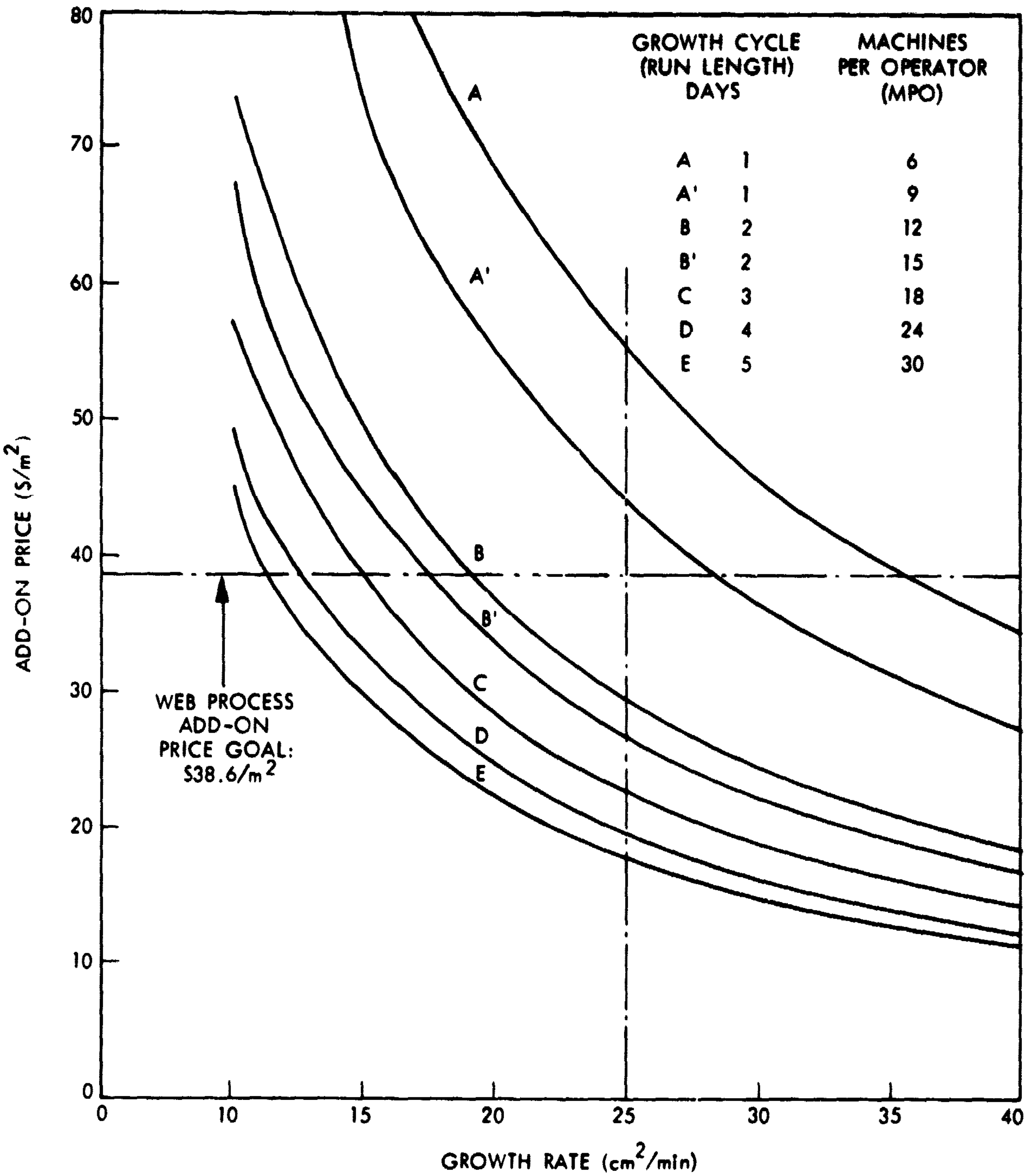

Figure 1. Add-on Price vs Web Process Growth Rate

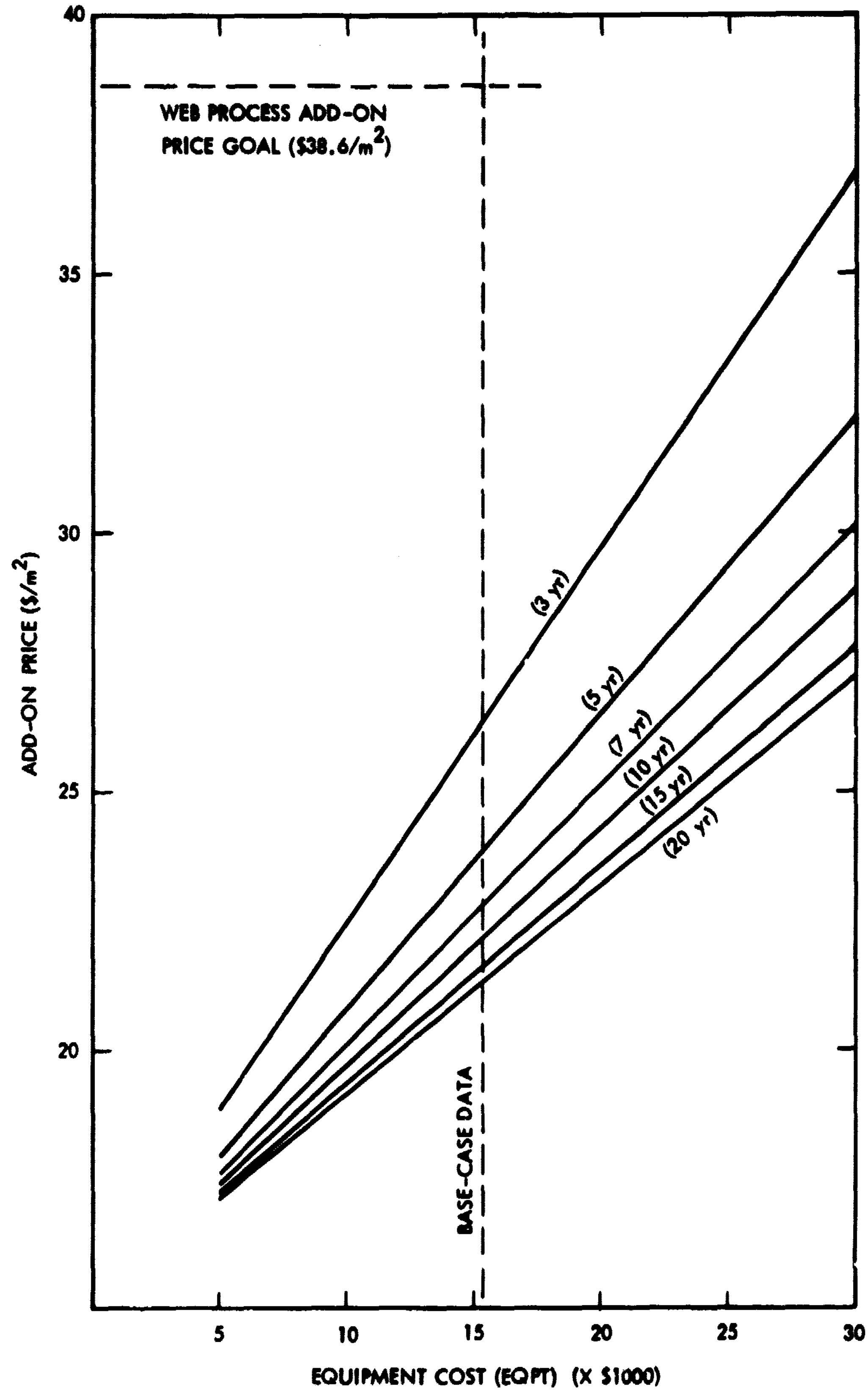

Figure 2. Add-on Price vs Web Process Equipment Cost

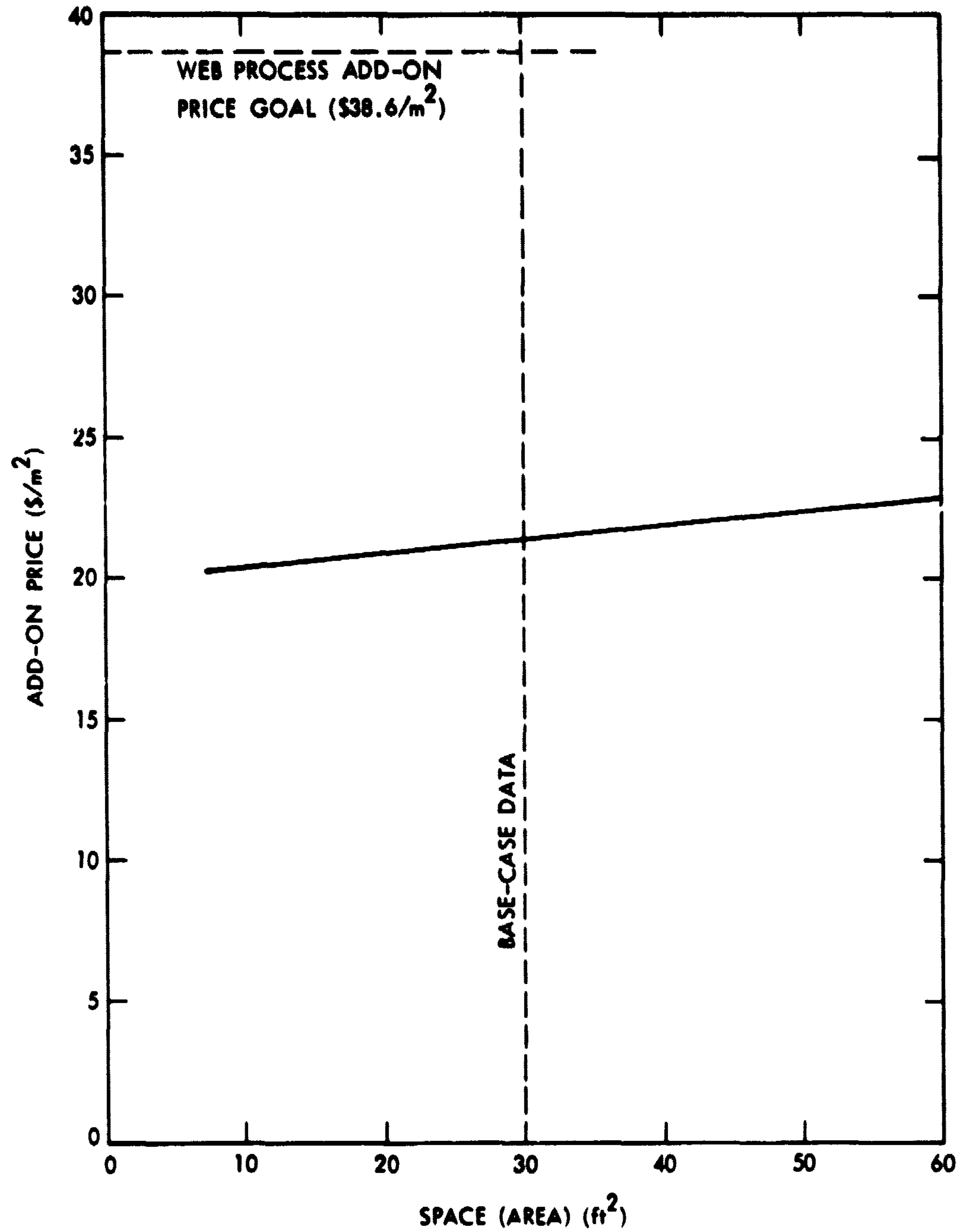

Figure 3. Add-on Price vs Web Process Equipment Area

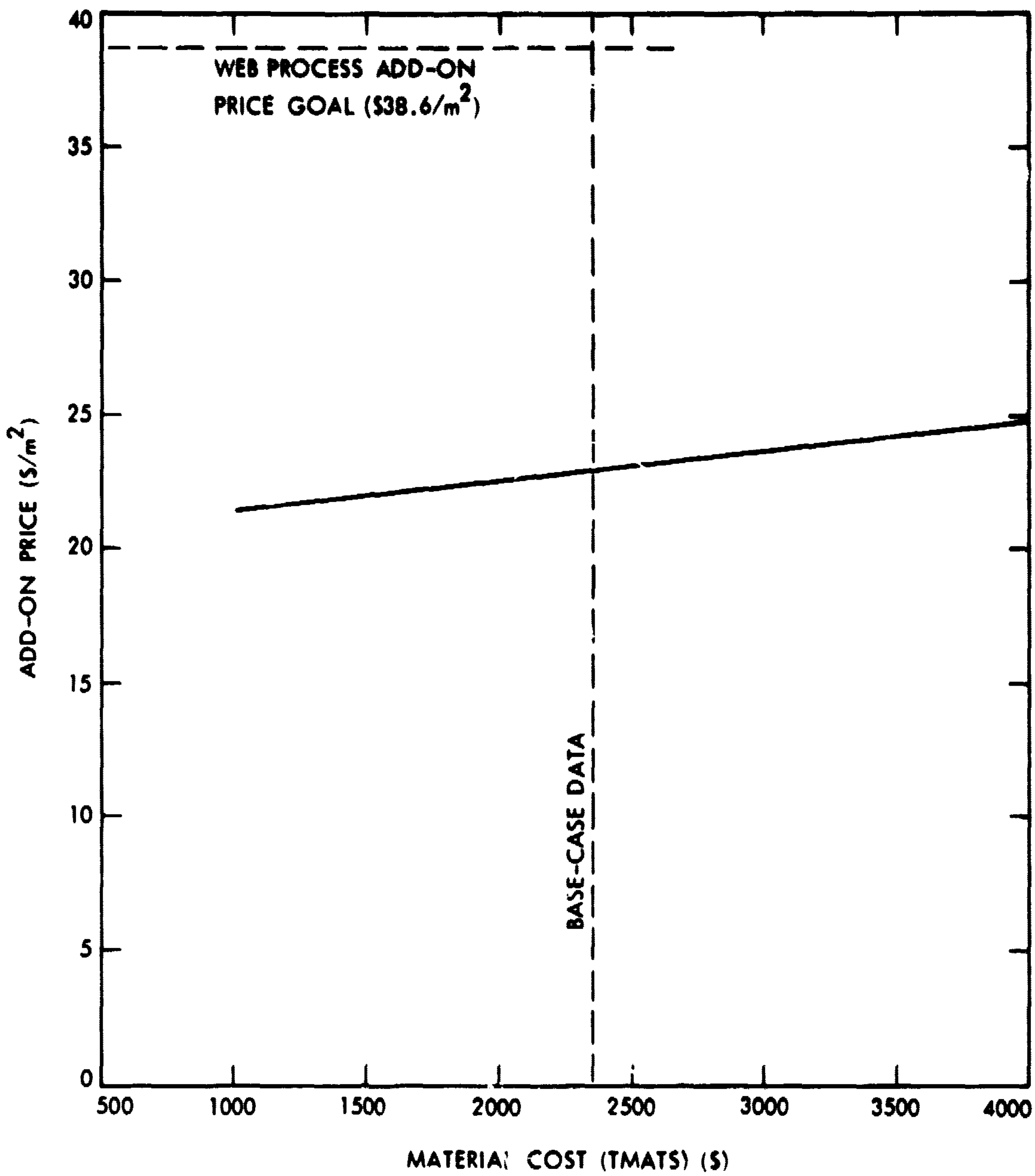

Figure 4. Add-on Price Web vs Process Direct Material Cost

The utilities cost varies from $500 to $3,000; the graph of utility cost vs add-on price is given in Figure 5. It may be observed that the utilities cost can go as high as $3,000 without exceeding the goal.

D. DIRECT LABOR COST

The base-case data have shown that direct labor is the primary cost driver, contributing 38% of the add-on price. The direct labor cost is a function of the labor pay rate and the number of furnaces operated by a single operator. The base case assumes an operator pay rate of $6.30/h (excluding fringe benefits) with one worker operating 18 furnaces. For the sensitivity analysis, the labor pay rate is varied from $5/h to $9/h (excluding fringe benefits). The number of furnaces operated by a single operator (FPO) is varied from 6 to 36 for each labor pay rate considered. The graphs of FPO vs add-on price are shown in Figure 6. It may be observed that the cost of direct labor is reduced considerably when FPO is increased from 6 to 24. The incremental decrease in the add-on price for FPO greater than 24 is negligible, as the curves are asymptotic. This suggests that efforts to automate the equipment in order to increase FPO should be limited to achieve FPO between 24 and 30. There is not much control over the labor pay rate, which is governed by external factors. Automation reduces the skills required and reduces the labor cost. For FPO of 18 the price goal is met with a labor pay rate of more than $9/h. It is also shown that the price goal is not met with FPO of 6 and labor pay rate as low as $6.30/h.

E. SILICON PRICE

The total add-on price of silicon sheet is the sum of the add-on price of the sheet process and of silicon material. The add-on price of the web process in $\$/m^2$ is converted to $\$/W_p$ with the known value of the insolation constant, sheet-to-cell yield and encapsulated cell efficiency. The add-on price of silicon in the cell in $\$/W_p$ is dependent (in addition to the above parameters) on sheet thickness and on silicon-to-sheet yield. For the purpose of the current study, the silicon-to-sheet yield is assumed to be a constant 90% and sheet to cell yield is assumed to be a constant 95%. The thickness of the sheet is varied from 2 mils to 8 mils with increments of 2 mils and the encapsulated cell efficiencies considered are 10% to 15%. Silicon price is varied from $15/kg to $85/kg with increments of $5/kg. For a given sheet thickness, the plot of silicon price vs add-on price in $\$/W_p$ is drawn with cell efficiency as a parameter. The results are presented in Figures 7a, 7b, 7c, and 7d for sheet thicknesses of 2 mils, 4 mils, 6 mils and 8 mils respectively.

It is observed that with sheet 2 mils thick (Figure 7a), the price goal is achieved with 10%-efficient cells for silicon prices as high as $75/kg. For higher-efficiency cells 2 mils thick, the silicon price will not interfere with achieving the goal. Four-mils-thick cells would achieve the goal with 10% cell efficiency and silicon price of $35/kg (Figure 7b); for 4-mils-thick cells with 14% or more efficiency, the silicon price is not a problem. For the 6-mil-thick sheet and cell efficiency of 10%, the price of silicon must not be more than $24/kg in order to achieve the goal (Figure 7c). With cells 6 mils thick with 15% efficiency, the silicon price can be as high as $65/kg. With 8-mils-thick cells and 10% efficiency, the silicon price should not be

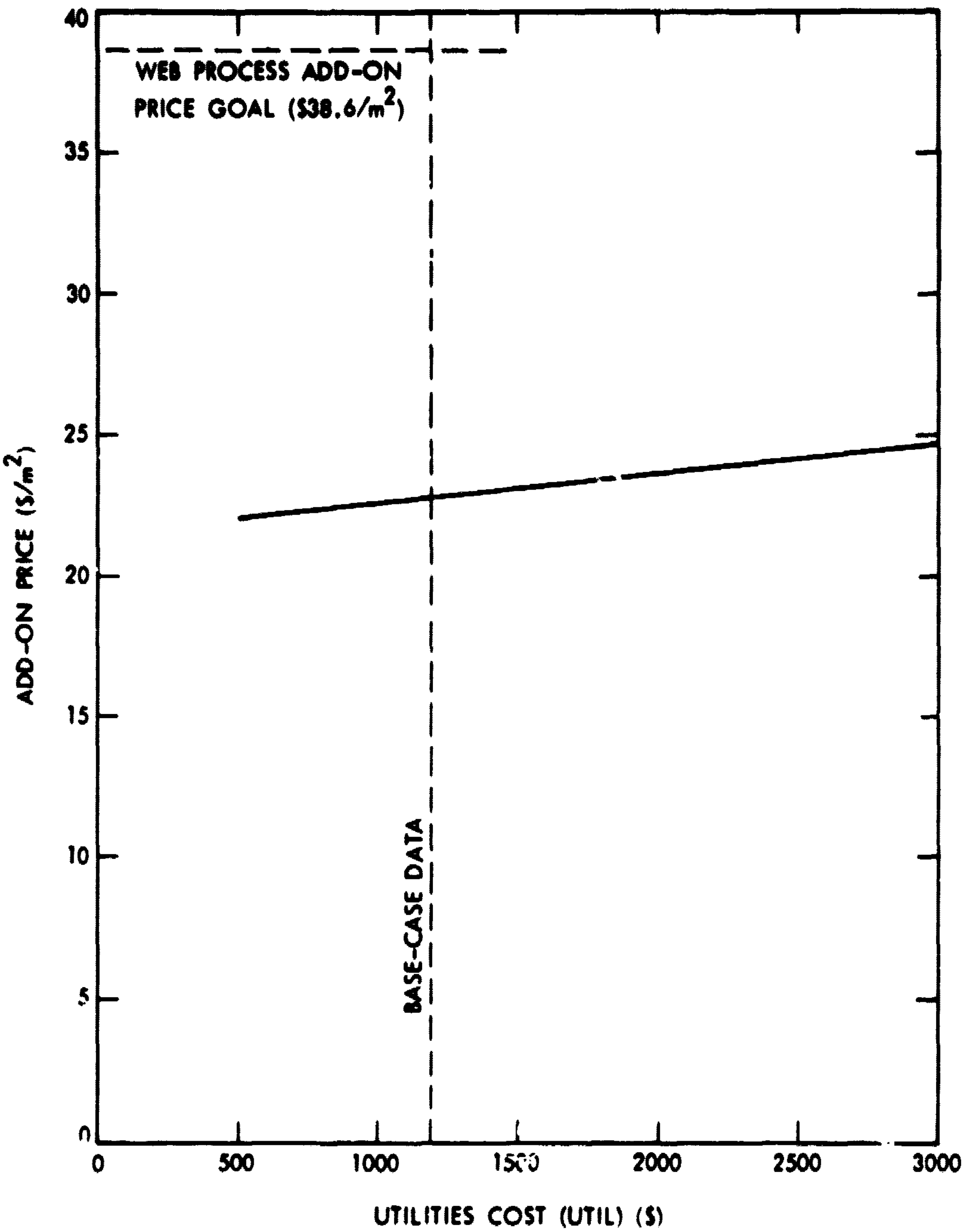

Figure 5. Add-on Price vs Web Process Utilities Cost

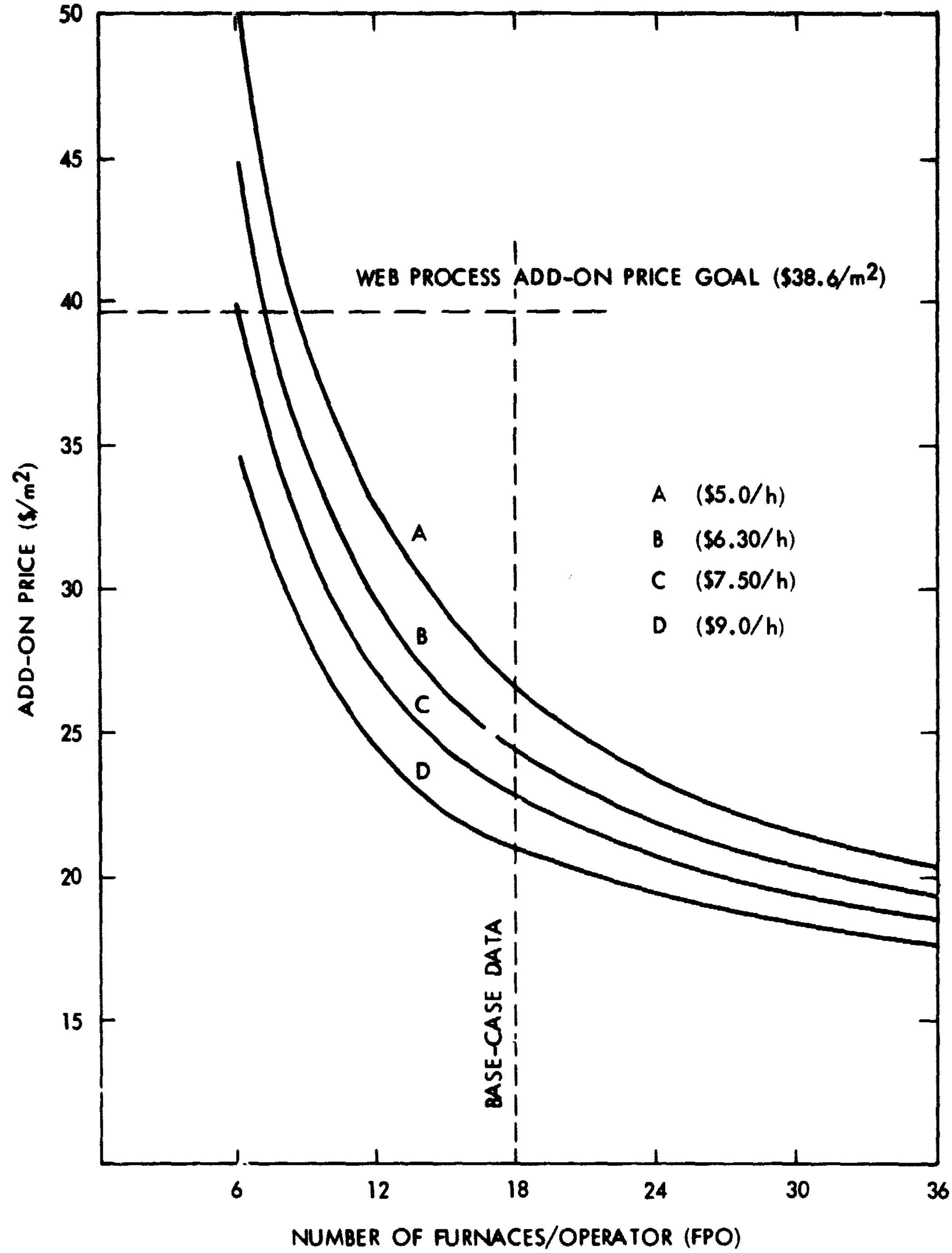

Figure 6. Add-on Price vs Web Process Direct Labor Cost

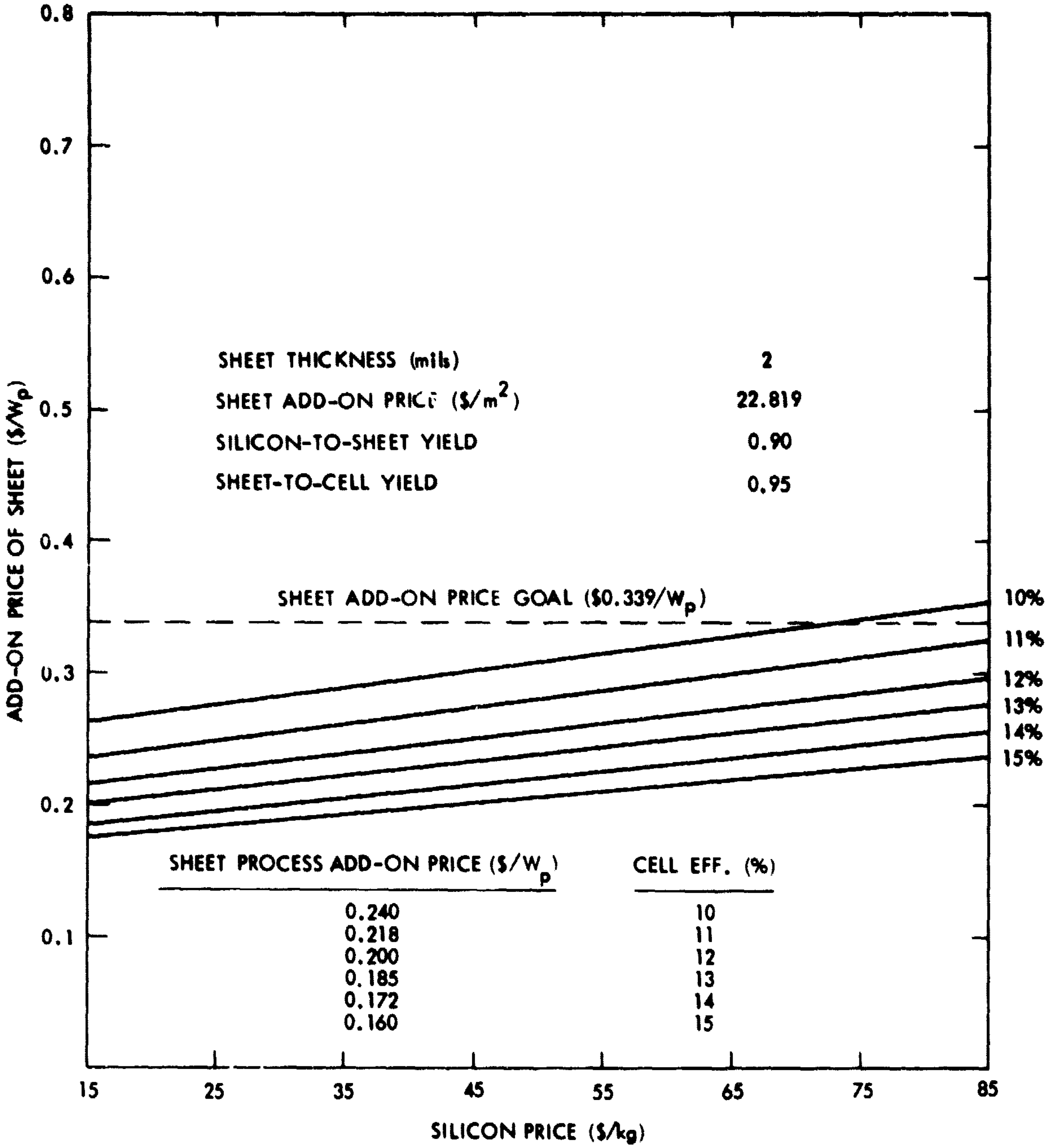

Figure 7a. Add-on Price vs Silicon Price for Sheet Using Web Process for Sheet Thickness of 2 mils

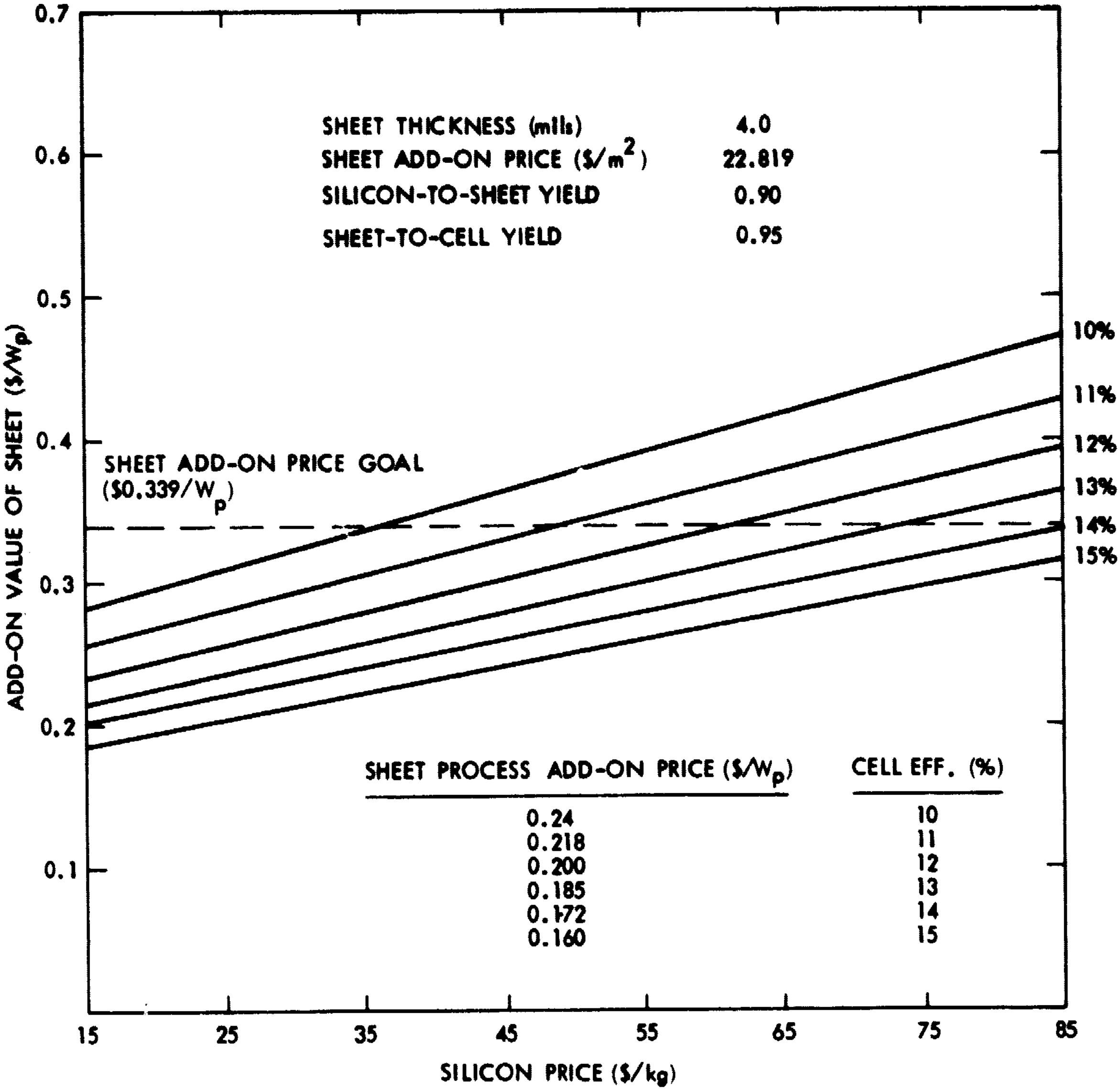

Figure 7b. Add-on Price vs Silicon Price for Sheet Using Web Process for Sheet Thickness of 4 mils

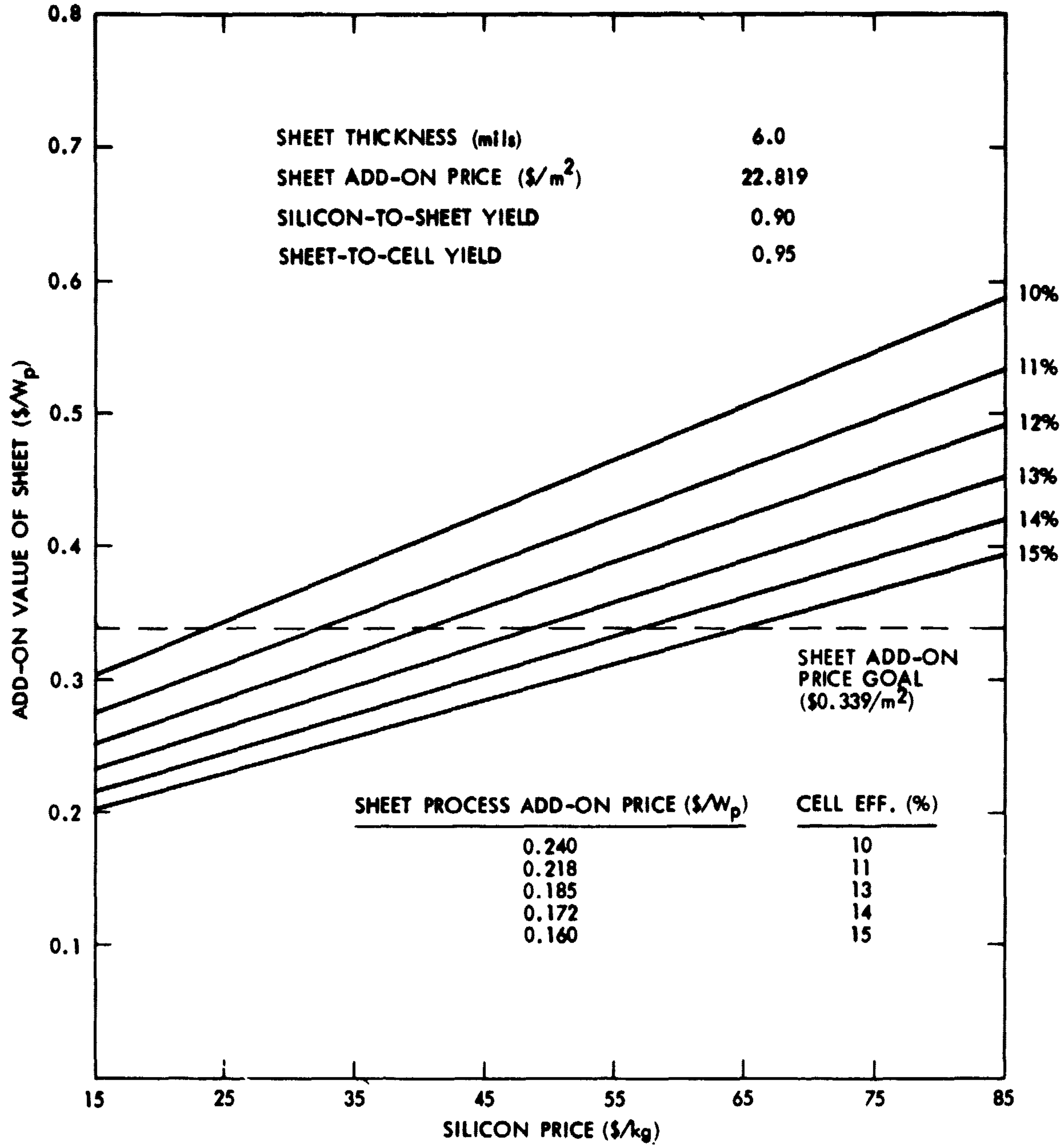

Figure 7c. Add-on Price vs Silicon Price for Sheet Using Web Process for Sheet Thickness of 6 mils

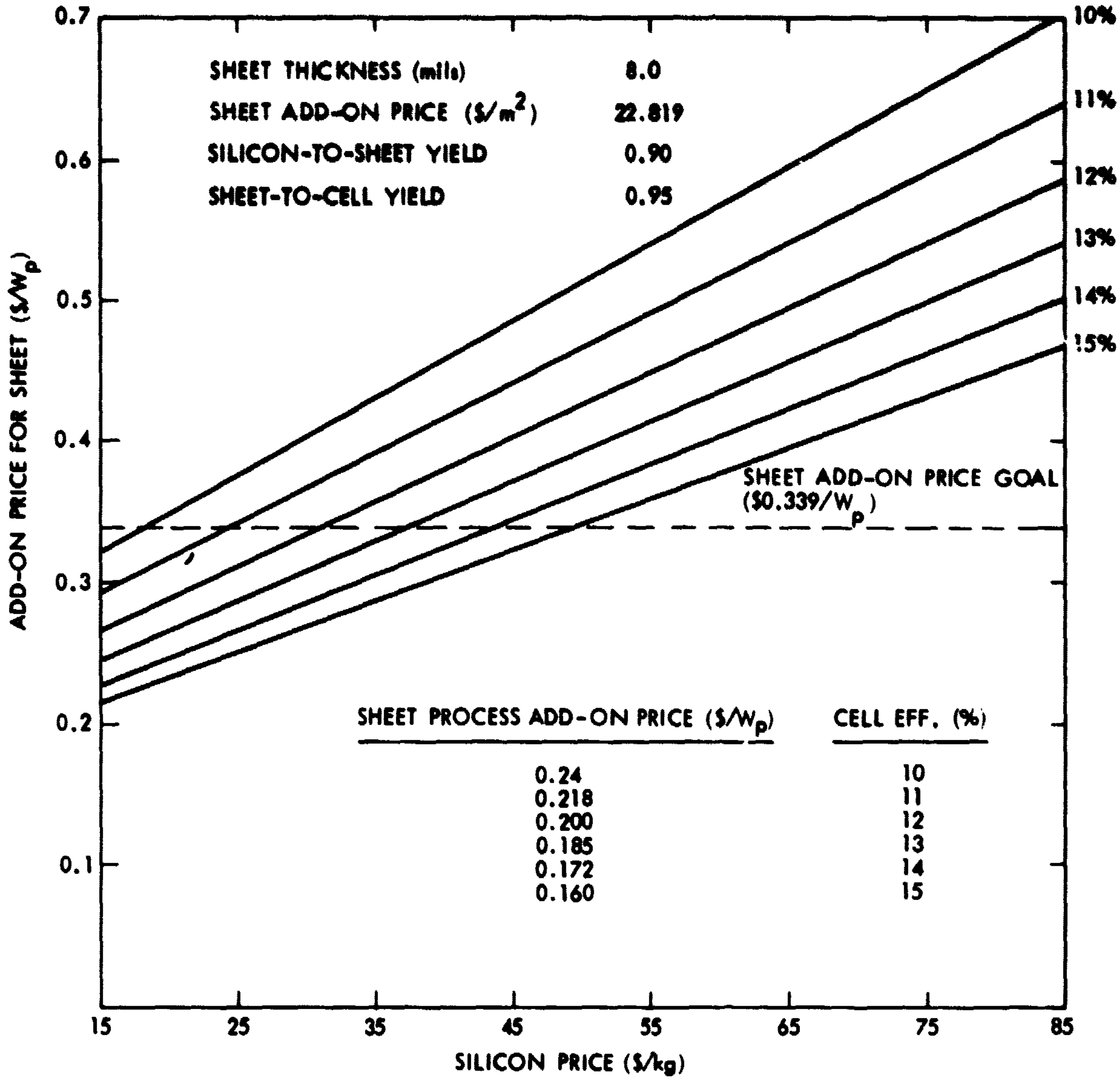

Figure 7d. Add-on Price vs Silicon Price for Sheet Using Web Process for Sheet Thickness of 8 mils

more than \$18/kg (Figure 7d); for 15%-efficient cells the silicon price can be as high as \$49/kg.

The silicon materials task goal is to achieve a silicon price of \$14/kg; the cell-efficiency goal for the web process is 14%. It is conceivable that the web process will not just achieve the goal of \$0.70/W_p, but surpass it. This technology has the potential of bringing the module price down to \$0.50/W_p.

SECTION V

CONCLUSIONS

The projected input data set for economic analysis by IPEG indicates that the add-on price goals can be easily met if all of the assumptions implied in the input data set are achieved. The ribbon-growth equipment is expected to operate on a continuous basis with melt replenishment, growing one ribbon 5 cm wide, at the rate of 5 cm/min. Each of these parameters, such as ribbon width and growth rate, has been shown to achieve the desired values independently. However, continuous steady growth of web at desired widths, speed, and run lengths has not been achieved. Efforts are being directed toward achieving this in order to attain Technical Readiness.

The add-on price breakdown indicates that the cost of direct labor is the primary cost driver, contributing 38% of the price; the cost of utilities is the weakest cost driver, contributing only 5% of the price. Efforts should therefore be directed to reduce the labor requirement by increasing automation. The sensitivity analysis indicates that it does not pay significantly to increase the number of furnaces tended by an operator to more than 24. The equipment cost contributes one third of the add-on price. It is worthwhile to work on minimizing that cost. For 6-in.-thick web sheet and 15% encapsulated cell efficiency, the silicon price can be as high as \$65/kg and still meet the price goal. By achieving growth of thinner sheets and lower prices for silicon, the web process technology can meet a $\$0.50/W_p$ goal.

The SAIPEG analysis is helpful in understanding the relative importance of the cost parameters and the add-on price sensitivity to each of them. This knowledge would be useful in planning efforts to improve the most sensitive cost parameters. The SAIPEG analysis should be performed on a continuous basis when results dictate modification of base-case input data.

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